THE ASTROPHYSICAL JOURNAL, 253:L49–L52, 1982 February 1

OBSERVATIONS OF RING STRUCTURE IN A SUNSPOT ASSOCIATED SOURCE AT 6 CENTIMETER WAVELENGTH

C. E. ALISSANDRAKIS
Astronomy Program, University of Maryland, and Laboratory of Astrophysics, University of Athens, Greece
AND
M. R. KUNDU
Astronomy Program, University of Maryland
Received 1981 August 31; accepted 1981 October 8

ABSTRACT

We report the detection of a new kind of sunspot associated source in which the emission comes predominantly from a ring structure with size between that of the umbra and the penumbra. The absence of emission from the center of the spot is interpreted in terms of the orientation of the magnetic field and the presence of low temperature material above the umbra.

Subject headings: Sun: radio radiation — Sun: sunspots

I. INTRODUCTION

The centimeter wavelength emission of solar active regions is an important diagnostic tool for understanding the physical conditions in these regions at the level of the lower corona and the chromosphere-corona transition zone. Observations of this emission provide good estimates of the electron temperature and are extremely useful for the study of magnetic fields which strongly influence the opacity of these regions. Thus, they can be used for studying the magnetic field configuration and obtaining estimates of the field strength in such regions as sunspots, plages, and loops.

Observations with aperture synthesis instruments (Kundu *et al.* 1977) have resulted in an improvement of the simple core-halo picture of an active region (Kundu 1959). The first observations with the Westerbork Synthesis Radio Telescope (WSRT) at 6 cm in 1974 showed the existence of four kinds of radio sources: (a) sources of high brightness temperatures ($T_b \sim 0.5 \times 10^6$ to 2.5×10^6 K) associated with sunspots; (b) weaker sources ($T_b \sim$ a few times 10^5 K) associated with regions of enhanced longitudinal magnetic fields in plages; (c) weaker sources associated with neutral lines and filaments (i.e., with regions of predominantly transverse magnetic fields); and (d) still weaker ($T_b \sim$ a few times 10^4 K) halo-type sources associated with plage regions.

The sunspot associated regions of enhanced 6 cm emission have been interpreted as arising from thermal gyroresonance emission (Zheleznyakov 1962; Kakinuma and Swarup 1962) at the second and third harmonic of the gyrofrequency. Detailed radiative transfer computations of the brightness distribution for one of the regions observed in 1974 (Alissandrakis, Kundu, and Lantos 1980) have shown that the gyroresonance process not only reproduces the brightness temperature of the source, but also the fine structure ($\sim 6''$) in both total intensity and circular polarization. The discrete sources in plages are probably due to third harmonic emission. In the case of sources associated with transverse fields, the emission may even be due to the fourth harmonic, since, as pointed out by Kundu *et al.* (1977), in such regions the angle between the magnetic field and the line of sight is $\sim 90°$ and, consequently, the absorption coefficient increases by several orders of magnitude compared to that at smaller angles. Thermal bremsstrahlung (free-free emission) may make some important contributions in these sources due to enhancements of electron density, and so may current sheets and temperature enhancements in loops (Zheleznyakov and Zlotnik 1980). However, detailed models for these types of sources have not been worked out yet. The weak emission is attributed entirely to free-free emission.

This picture of active region structure has been confirmed by more recent high resolution observations with the Very Large Array (VLA) (e.g., Kundu, Schmahl, and Rao 1981; Lang and Willson 1980), although in several cases the emission associated with the transverse magnetic field far exceeded the sunspot associated emission (Kundu, Schmahl, and Rao 1981). A spectacular "loop" structure has also been observed (Kundu and Velusamy 1980) extending along an Hα filament. We should also refer to the absence of strong sunspot associated emission at 6 and 2.8 cm in the case of spots with overlying low temperature material (Pallavicini 1980; Kundu, Schmahl, and Rao 1981).

It is important to note that at 6 cm the second harmonic comes from a magnetic field level of 900 gauss, the third from the 600 gauss level, and the fourth from the 450 gauss level. Thus, if the emission is due to gyroresonance emission, a fairly accurate estimate of the magnetic field can be made in solar atmospheric regions not easily accessible for field measurements by other means.

In this *Letter* we report the detection of a new kind of sunspot associated emission, confined near the sunspot penumbra, and we discuss the results in terms of physical conditions in the transition zone and corona above the spot.

II. OBSERVATIONS AND DATA REDUCTION

The observations were obtained at 6.16 cm (4874 MHz, bandwidth 10 MHz) with the WSRT during 1980 May 22–27. Approximately 12 hours of observations were used daily to produce full synthesis maps in Stokes parameters I (total intensity) and V (circular polarization) with an E-W resolution of 3″.6–4″.2 and a N-S resolution of 10″–12″.2. Sources that show time variations on a scale of less than 12 hours will be distorted in the maps (see Kundu *et al.* 1977); however, most of the strong sources were found to be stable throughout the observing period. The shortest baseline was 54 m (1877 λ), the longest 2718 m (44160 λ), making the instrument most sensitive to sources with E-W sizes between 2″ and 1′.7 and N-S sizes between 5″.8 and 5′.0. The baseline increment was 72 m (1170 λ) so that the innermost grating ring had a diameter of 5′.19 (E-W) by 17′.1 (N-S).

The observing procedure was similar to the one for our 1974 observations (Kundu *et al.* 1977) and has been described in detail by Bregman (1980).

For the data reduction we followed the procedure of the 1974 observations except in one respect. The sources in the dirty maps were so extended that the normal CLEAN procedure of decomposing them into point sources did not work. Therefore the cleaning of the dirty maps was performed as follows: (a) a low resolution map was computed and decomposed into individual sources; (b) these sources were subtracted from the visibility before performing the Fourier transforms; (c) the resulting dirty maps, which contained only small-scale components were cleaned using the CLEAN procedure; and (d) the subtracted sources were added back into the clean map.

III. RESULTS AND DISCUSSION

We observed three active regions, Hale Nos. 16862, 16863, and 16864 (Fig. 1) at a heliographic longitude of about 50° E until 1 day after their central meridian passage (CMP). The regions 16863 and 16864 contained one large sunspot each (penumbral diameter ~ 70″) of negative polarity (Fig. 2) as well as a large number of smaller spots and pores distributed over the following parts of the regions. The magnetic configuration was complex, with small patches of opposite polarity surrounding the large spots. The region 16862 had a simpler structure, with two well-developed spots of opposite polarity. The longitudinal component of the photospheric field in the largest sunspot of each region reached values of 2600–3000 gauss (*Solar-Geophysical Data* 1980).

The total intensity map for May 25 is shown in Figure 1*a* (Plate L1) superposed on an Hα photograph from the observatory at Athens and in Figure 2*a* (Plate L3) superposed on a Kitt Peak magnetogram. The positions of the center of the field halfway during the observations was at E08, S16, the heliocentric distance being 18°. The region 16864 (Fig. 1*a*) shows a prominent ring structure (a) associated with the main spot, an elongated source (b) extending along an Hα filament, and some diffuse emission (c) in the following part of the region. The rim of the ring source does not have a uniform intensity, but its brightness temperature, T_b, ranges from 1.5×10^6 to 2.5×10^6 K while at its center it drops to less than 5×10^5 K. The diameter of the ring measured between the points of maximum intensity is about 50″, which is intermediate between the diameters of the umbra and the penumbra of the spot. The source associated with the elongated filament extends from the penumbra of the spot in the NE direction and has three distinct components with $T_b \approx 3 \times 10^6$ K; the southernmost part of the source is located near a smaller spot sharing a common penumbra with the large spot and extends eastward along the direction of a second Hα filament.

The region 16863 shows a much more complex structure (Fig. 1*a*). A well-defined source is observed in the eastern part (source A) with $T_b \approx 10^6$ K, associated with a small spot of following polarity. To its west lies a broad source (B) associated with a group of pores with $T_b \sim 1.5 \times 10^6$ K; this is followed by the strongest source (C) in the field of view ($T_b = 3.8 \times 10^6$ K), which is associated with an Hα filament located in the N-S direction. The emission associated with the large spot is not uniform and it does not have a clear ring structure either; the brightest component (D) with brightest temperature $\sim 3.6 \times 10^6$ K appears to be associated with a long-lived Hα brightening located above the umbra, while other components are associated with the penumbra. With the exception of source A, the entire active region is embedded in a region of diffuse emission with $T_b > 5 \times 10^5$ K. This emission extends even up to the source associated with the following spot of region 16862 (source α), although there is very little Hα plage emission between sources D and α. The magnetogram (Fig. 2*a*) shows some patches of opposite polarities in this region so that one would expect that low-lying loop structures should exist there; it is therefore possible that the diffuse emission originates in such

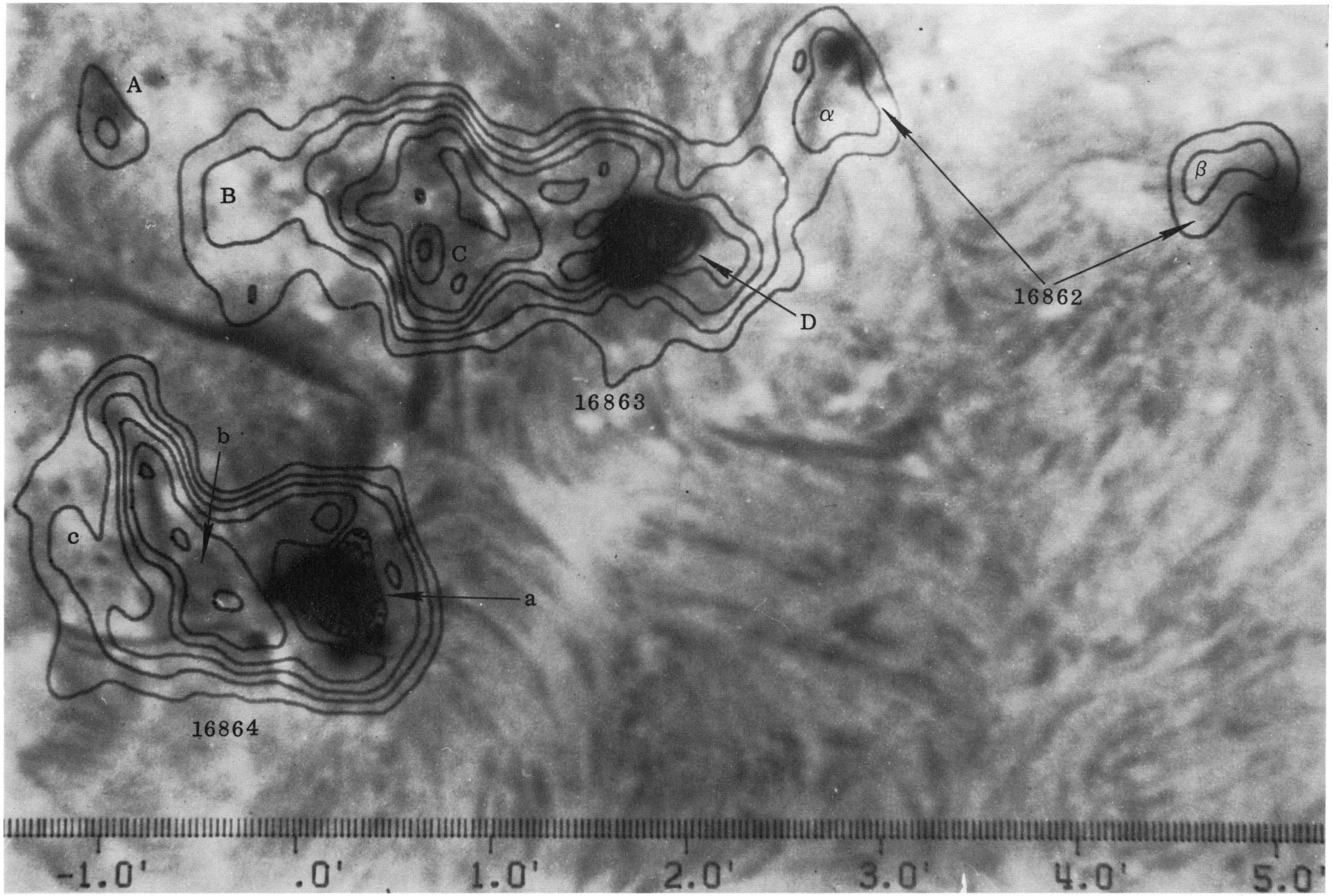

FIG. 1*a*

FIG. 1.—Total intensity (*a*) and circular polarization (*b*) contours for 1980 May 25 at 6.16 cm overlaid on an Hα photograph obtained from the observatory at Athens. Three active regions are included in the field of view. The contours are in steps of 5×10^5 K for the total intensity and 1.5×10^5 K for the circular polarization. Hatched contours show decreasing brightness temperature. The scale is in minutes of arc.

ALISSANDRAKIS AND KUNDU (*see* page L50)

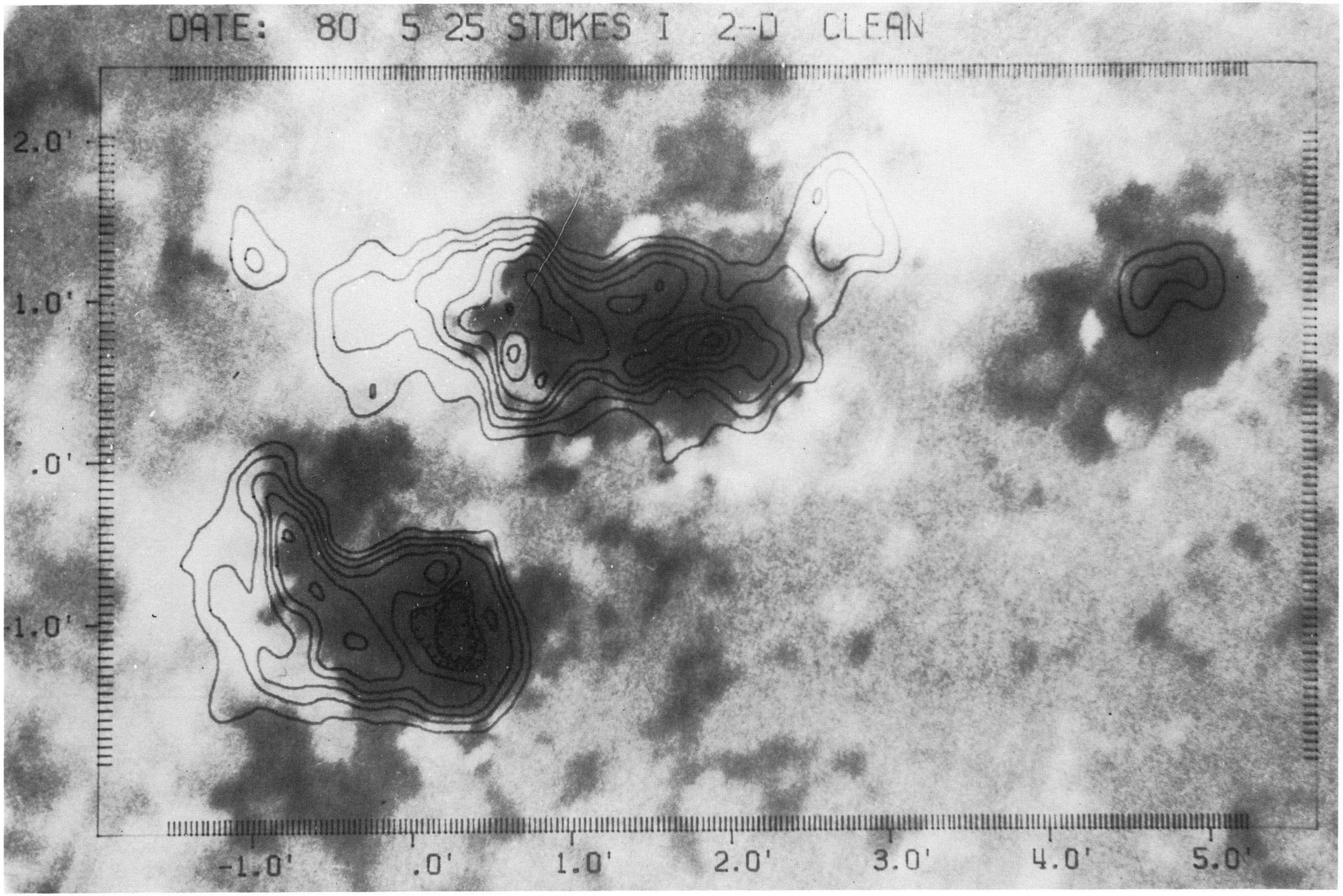

FIG. 2*a*

FIG. 2.—Total intensity (*a*) and circular polarization (*b*) maps for 1980 May 25 overlaid on a Kitt Peak magnetogram (courtesy of J. Harvey). Black regions indicate negative polarity.

ALISSANDRAKIS AND KUNDU (*see* page L50)

loops, although they are not resolved in the map. This is further supported by the fact that the 5×10^5 K level is above the normal plage emission, as evidenced by the absence of such strong emission in association with the Hα plage between source α and source β; the latter, with $T_b \sim 10^6$ K, is associated with the preceding spot of region 16862.

The circular polarization map of the same region is shown in Figures 1*b* and 2*b* (Plates L2 and L4). The most striking feature is that practically all of the polarized emission shows left circular polarization which corresponds to the extraordinary mode in the region of negative (black) magnetic polarity.

A comparison of the *I* and *V* maps shows that the strongest emission peaks are weakly polarized, whereas the most prominent peaks of the *V* map occur at the slopes of strong sources, where the degree of polarization reaches $\sim 80\%$. Such high polarization, both for sunspot and filament associated sources, is strong evidence that the emission is due to the gyroresonance process in both cases. We note that the circular polarization is low at the location of the total intensity peaks. This effect may be due to the high opacity of these peaks and to the location of the gyroresonance emission layers higher in the atmosphere where the temperature gradient is small (cf. Alissandrakis, Kundu, and Lantos 1980). An alternative interpretation, valid for sources located near regions of polarization inversion, is the depolarization of the radiation as a result of Q-T propagation; indeed, computations by Zheleznyakov and Zlotnik (1963) showed that near the "critical frequency" part of the circularly polarized radiation becomes linearly polarized.

The newly discovered ring structure could be produced as a result of the low gyroresonance opacity when the angle between the magnetic field and the line of sight is close to zero; such a structure (Zheleznyakov 1970) should exist above the center of a sunspot located near the center of the disk so that the orientation of the magnetic field is predominantly longitudinal. Since, under conditions prevailing above spots, the region of small opacity is very small for the second harmonic and more extended for the third, one expects a decrease in total intensity in such regions (Alissandrakis 1980; Gel'freikh and Lubyshev 1979). The region of low intensity should shift toward the center of the disk with respect to the region of most intense 6 cm emission as it moves toward the limb. At large distances from the center, the low intensity region is located outside the penumbral border, and the region becomes crescent shaped, oriented parallel to the limb. The location of the intensity dip as well as the overall structure do not change much over the 6 days of our observations (Fig. 3), although the heliocentric distance varies from $\sim 52°$

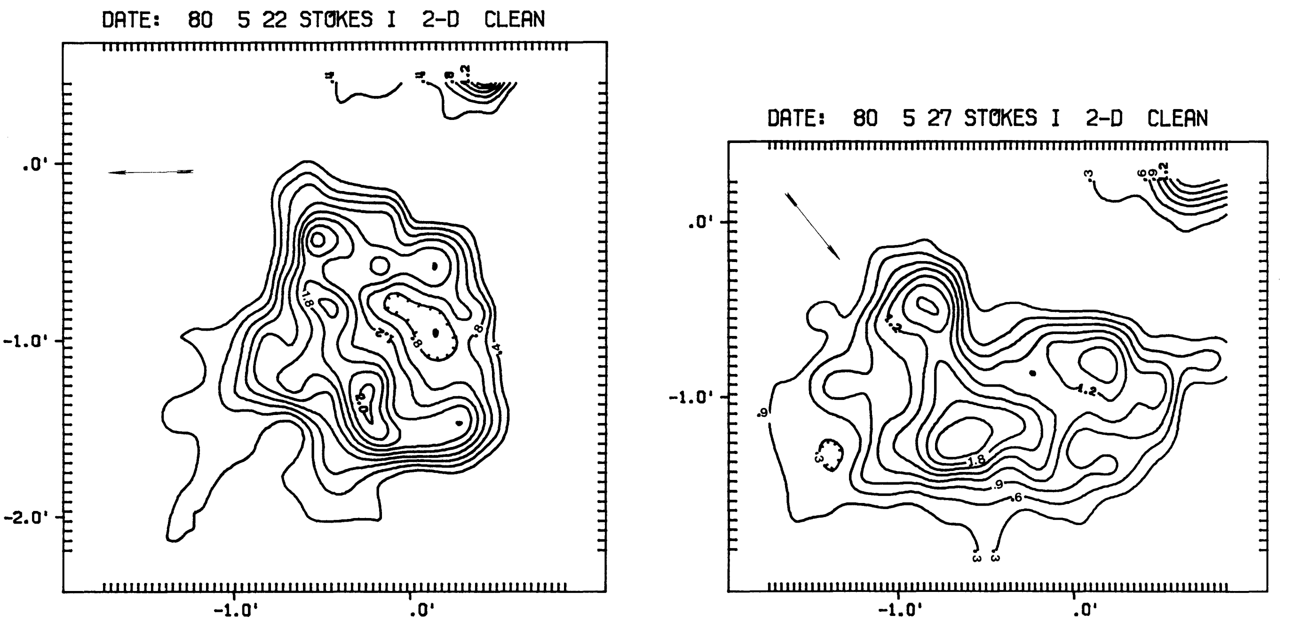

FIG. 3*a* FIG. 3*b*

FIG. 3.—(*a*) and (*b*) Total intensity contour maps of region 16864 with the sunspot associated ring source, 1980 May 22 and 27. On May 22, in the middle of the observing period, the center of the spot was at E50, S20 (heliocentric distance 52°), while on May 27 it was W14, S20 (heliocentric distance 24°). Notice the persistence of the low intensity region above the center of the sunspot (cf. Figs. 1 and 2) despite the change of the direction of the limb (indicated by arrows) and the change of the heliocentric distance. The contour labels show the brightness temperature in units of million degrees.

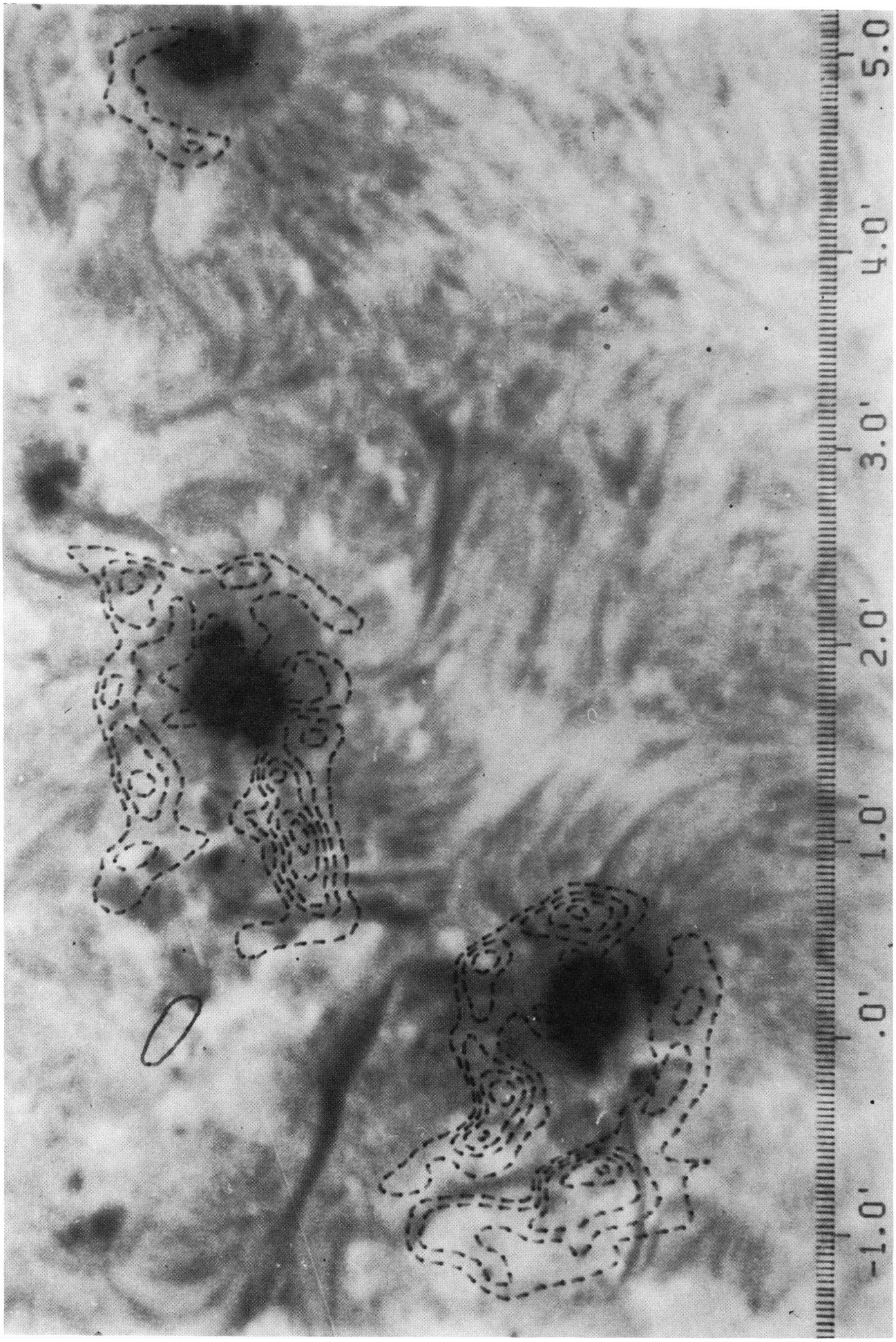

FIG. 1b

ALISSANDRAKIS AND KUNDU (*see* page L51)

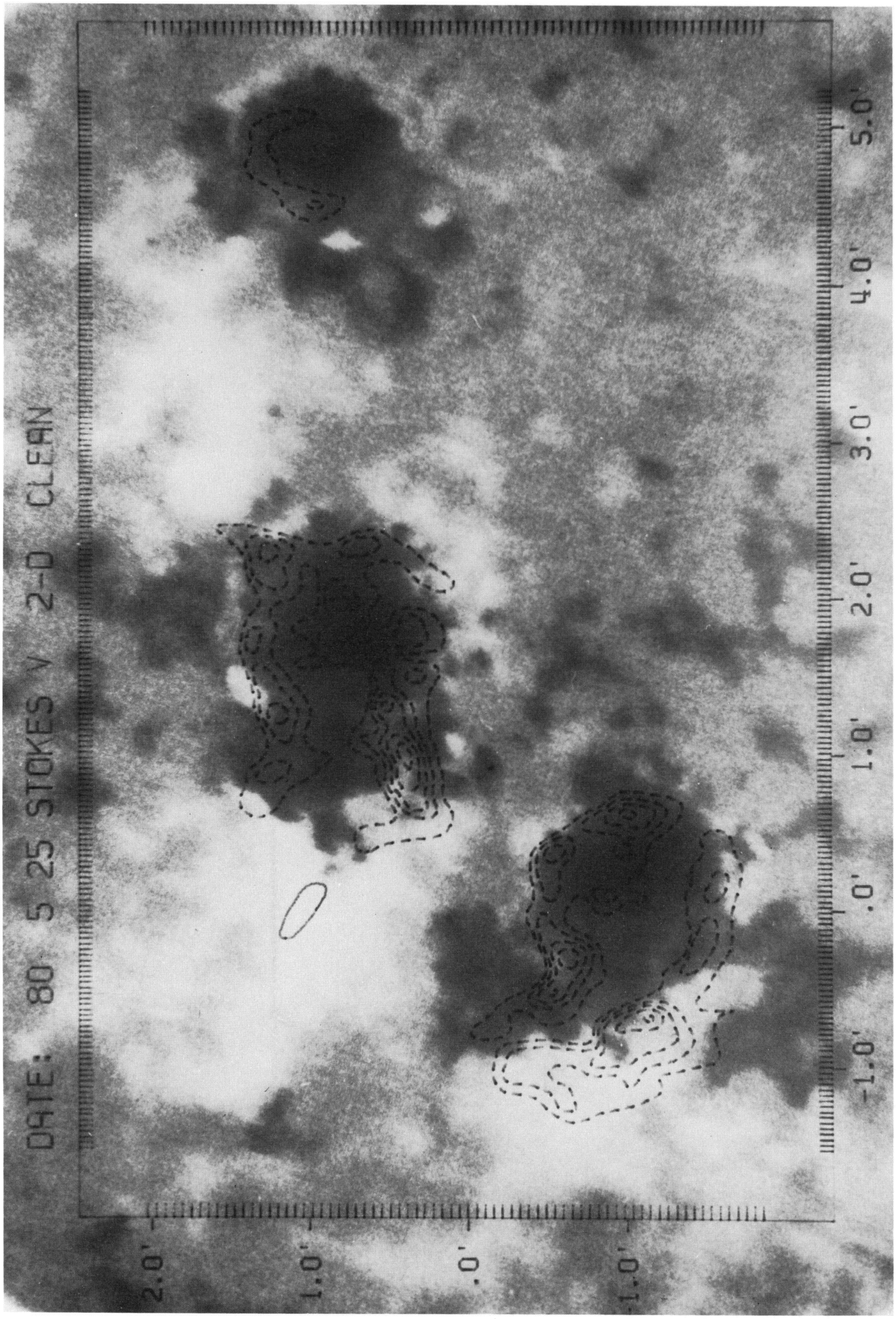

FIG. 2b

ALISSANDRAKIS AND KUNDU (*see* page L51)

to 20° (at CMP) and then to 24°, and the direction of the limb changes drastically. The behavior of the region far from the center of the disk can be understood if we assume that, in addition to the angle effect, there is a temperature decrease above the umbra at the level of formation of the radiation.

We should note that from EUV observations Foukal *et al.* (1974) and Nicholas *et al.* (1981) have pointed out the existence of low temperature flux tubes above some sunspots. There was no evidence of such low temperature regions in our early WSRT observations (see discussion by Alissandrakis, Kundu, and Lantos 1980), either because of poorer spatial resolution or, most probably, due to the absence of such low temperature regions from those particular sunspots. However, from higher resolution observations using the VLA, Kundu and Velusamy (1980) and Kundu, Schmahl, and Rao (1981) demonstrated the lack of correlation between the umbra and strong 6 cm emission and attributed it to the existence of similar cool material. Felli, Lang, and Willson (1981) have also shown that the sunspot associated 6 cm emission of another active region is concentrated in hot ($\sim 10^6$ K), highly circularly polarized ($\approx 90\%$) sources which lie at the outer edges of the sunspot and not above the umbra.

We believe that the present radio observations are the first to show the existence of ring structure in the brightness distribution of an active region at 6 cm. We attribute it to either the low gyroresonance opacity at the spot center near its central meridian passage or to cool material above sunspots or to a combination of both effects. The question might be resolved by detailed model computations.

IV. SUMMARY AND CONCLUSIONS

Our observations have shown that a bright ring can exist in the structure of a sunspot associated 6 cm region whose diameter lies between that of the penumbra and umbra of the sunspot. This structure is interpreted as being due to the low gyroresonance opacity at the spot center near the central meridian passage or the presence of cool material ($\sim 5 \times 10^5$ K) in the upper transition region and low corona above the spot. These sunspot associated components have brightness temperatures lying between 10^6 and 3.3×10^6 K. The brightest sources ($3–3.8 \times 10^6$ K) observed by us are associated with neutral lines and their corresponding Hα filaments, while the diffuse emission presumably originating in unresolved hot loops has temperatures $> 5 \times 10^5$ K.

The authors are grateful to Dr. J. Harvey for the magnetogram. One of the authors (C. E. A.) wishes to acknowledge a travel grant from the IAU. This research at the University of Maryland was supported by NASA grant NGR 21-002-199, NASA contract NSG 5320, and NSF grant ATM 78-21762. The computations were done with a grant from the University of Maryland's Computer Science Center.

We thank the Observatory of Athens for providing the Hα pictures.

REFERENCES

Alissandrakis, C. E. 1980, in *IAU Symposium 86, Radio Physics of the Sun*, ed. M. R. Kundu and T. E. Gergely (Dordrecht: Reidel), p. 101.
Alissandrakis, C. E., Kundu, M. R., and Lantos, P. 1980, *Astr. Ap.*, **82**, 30.
Bregman, J. D. 1980, *Netherlands Foundation for Radio Astronomy Report*, No. 330.
Felli, M., Lang, K. R., and Willson, R. F. 1981, *Ap. J.*, **247**, 325.
Foukal, P. V., Huber, M. C. E., Noyes, R. W., Reeves, F., Schmahl, E. J., Timothy, J. G., Vernazza, J. E., and Withbroe, G. L. 1974, *Ap. J. (Letters)*, **193**, L143.
Gel'freikh, G. B., and Lubyshev, B. I. 1979, *Astr. Zh.*, **56**, 562 (*Soviet Astr.—AJ*, **23**, 316).
Kakinuma, T., and Swarup, G. 1962, *Ap. J.*, **136**, 975.
Kundu, M. R. 1959, *Ann. d'Ap.*, **22**, 1.
Kundu, M. R., Alissandrakis, C. E., Bregman, J. D., and Hin, A. C. 1977, *Ap. J.*, **213**, 378.
Kundu, M. R., Schmahl, E. J., and Rao, A. P. 1981, *Astr. Ap.*, **94**, 72.
Kundu, M. R., and Velusamy, T. 1980, *Ap. J. (Letters)*, **240**, L63.
Lang, K. R. and Willson, R. F. 1980, in *IAU Symposium 86, Radio Physics of the Sun*, ed. M. R. Kundu and T. E. Gergely (Dordrecht: Reidel), p. 109.
Nicholas, K. R., Kjeldseth-Moe, O., Bartoe, J. D. F., and Brueckner, G. E. 1981, *Solar Phys.*, in press.
Pallavicini, R. 1980, in *IAU Symposium 86, Radio Physics of the Sun*, ed. M. R. Kundu and T. E. Gergely (Dordrecht; Reidel), p. 119.
Solar-Geophysical Data. 1980, No. 430, part I (Boulder: NOAA Environmental Data and Information Service).
Zheleznyakov, V. V. 1962, *Astr. Zh.*, **39**, 5 (*Soviet Astr.—AJ*, **6**, 3).
______. 1970, *Radio Astronomy of the Sun and Planets* (New York: Pergamon).
Zheleznyakov, V. V., and Zlotnik, E. Ya. 1963, *Astr. Zh.*, **40**, 663 (*Soviet Astr.—AJ*, **7**, 485).
______. 1980, *Astr. Zh.*, **57**, 778 (*Soviet Astr.—AJ*, **24**, 448).

C. E. ALISSANDRAKIS and M. R. KUNDU: Astronomy Program, University of Maryland, College Park, MD 20742